



Silicon-nanocrystal Optoelectronic Kerr Effect for Complementary Metal-oxide Semiconductor (CMOS) Compatible Optical Switching

by Neal K. Bambha, Justin R. Bickford, and Stefan F. Preble

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14. ABSTRACT There is a broad Army need to quickly transfer large amounts of data from sensors to processors on a wide variety of systems. Complementary metal-oxide semiconductor (CMOS) compatible optical intra-chip data communication systems would enable this data flow by increasing data rates and reducing circuit size and power. We investigated the fabrication of a monolithic CMOS-compatible optoelectronic silicon (Si) modulator for intra-chip communication. The modulator is designed to take advantage of the large Kerr effect that has been reported in Si-nanocrystals imbedded in oxide (Si-nc). The expected refractive index change versus applied voltage was calculated for the design, and an index change of $\sim 2 \times 10^{-4}$ is enough to modulate the light, corresponding to a voltage of only 0.5–1.5 V. Confinement of light in the waveguide and microdisk is accomplished via a slot waveguide design. Several samples of Si-rich oxide films were deposited by reactively sputtering Si in the presence of oxygen, plasma enhanced chemical vapor deposition (PECVD), and low pressure chemical vapor deposition (LPCVD), as well as spin casting of hydrogen silsesquioxane (HSQ). The nonlinear index of these samples was characterized by an optical Z-scan measurement using a short pulse fiber laser with a 1.5- μm wavelength.					
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1. Objective

Current computing systems, such as field programmable gate arrays (FPGAs), graphical processor units (GPUs), and multi-core processors, are reaching their inter- and intra-chip data communication limits. Current links are based on copper transmission lines, which limit data capacity and speed, and are now dominating these systems' power and space budgets. There is a broad Army need to quickly transfer large amounts of data from sensors to processors on a wide variety of systems. Such systems will find use in future embodiments of current program elements, such as advanced tactical computer science and sensor technology, unmanned ground vehicles, tactical unmanned aerial vehicles, and airborne reconnaissance systems. Leaps in intra-chip communication technology will significantly improve computing performance and allow processors to perform previously unrealizable feats for these applications. Complementary metal-oxide semiconductor (CMOS) compatible optical intra-chip data communication systems would advance computing system performance/size-weight-power by increasing data rates and reducing circuit size and power.

We investigated the fabrication of a monolithic CMOS-compatible optoelectronic modulator in silicon (Si). The large Kerr effect of Si-nanocrystals imbedded in oxide (Si-nc) (*1*) may be used in an optical modulator, which could operate at high-speeds (up to 100 Gbit/s) with low switching voltage (~ 1 V). This device could be used in a system with several optical wavelengths, giving it the ability to multiply communication capacity via wavelength-division multiplexing (WDM); see figure 1 for an illustration of a WDM optical link. The anticipated improvements of this device over existing electronic switching would significantly advance next-generation processors.

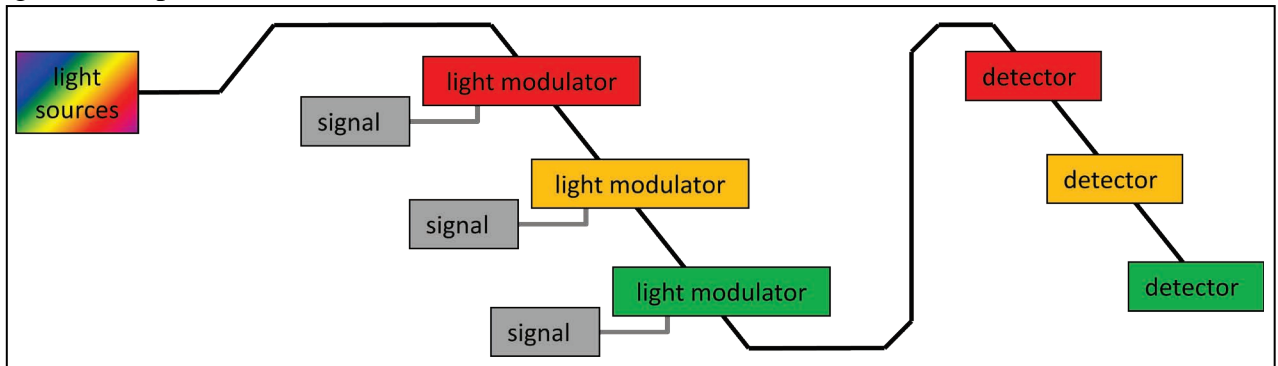


Figure 1. Proposed Si-based WDM optical link.

2. Approach

Optical data communications systems require three devices: a light source, a modulator, and a detector—our proposed work focuses on the optical modulator. Traditional modulators are implemented in direct bandgap semiconductor materials such as indium gallium arsenide phosphide (InGaAsP) or electro-optic materials such as lithium niobate (LiNbO₃). These materials have a long history of optimization, but their integration into standard Si CMOS processing has lagged far behind. A high-yield integration scheme has yet to be commercially implemented. The ultimate integration method would involve some form of Si itself as the active optical material. Since crystalline Si is an indirect bandgap material, its band-to-band optical absorption is not as efficient as direct bandgap materials, nor would its bandgap be suitable for traditional 1.55 μm wavelength light. Therefore, research has thus far focused on using free-carrier plasma dispersion as an alternative (2–5). This method absorbs light, which changes the material’s index of refraction via dispersion. This absorption requires carrier transport and, in present implementations, suffers from slow minority carrier diffusion. Reducing the active thickness over which the carriers must diffuse in an attempt to improve speed reduces the strength of the effect, trading efficiency for speed.

The proposed research focuses on the electro-optic effect, which changes a material’s index of refraction via an applied electric field according to equation 1. The traditional electro-optic effect used in optical modulators is the linear Pockels effect, which is related to the constant s_1 , while the second (usually weaker) Kerr effect is related to the constant s_2 .

$$\Delta n = s_1 E + s_2 E^2 \quad (1)$$

Unfortunately, in unstrained crystalline Si, no Pockels effect exists and the Kerr effect is very small. However, a notably large Kerr effect of $\sim 2 \times 10^{-12} \text{ cm}^2/\text{W}$ has been found in Si-nc (1). The Si-nc layer would be fabricated using equipment at the Rochester Institute of Technology (RIT) and the U.S. Army Research Laboratory (ARL) by depositing a Si-rich oxide film and coalescing the Si agglomerations into nanocrystalline particles via annealing. Films will be characterized via photoluminescence, transmission electron microscopy (TEM), and nonlinear optical measurements. The proposed microdisk resonator modulator is shown in figure 1 and illustrates how contacts (gold) would change the electric field in the Si-nc film (blue-gray)—sandwiched between the Si layers (red). An oxide layer (light gray) separates the active device layers from the Si substrate (green). Light enters the waveguide on the right and is alternately exchanged between the microdisk resonator and the output of the waveguide. Figure 2 shows an estimate of the expected refractive index change versus applied voltage. An index change of $\sim 2 \times 10^{-4}$ is enough to modulate the light, corresponding to a voltage of only 0.5–1.5 V. Confinement of light in the waveguide and microdisk is accomplished via a slot waveguide design (6).

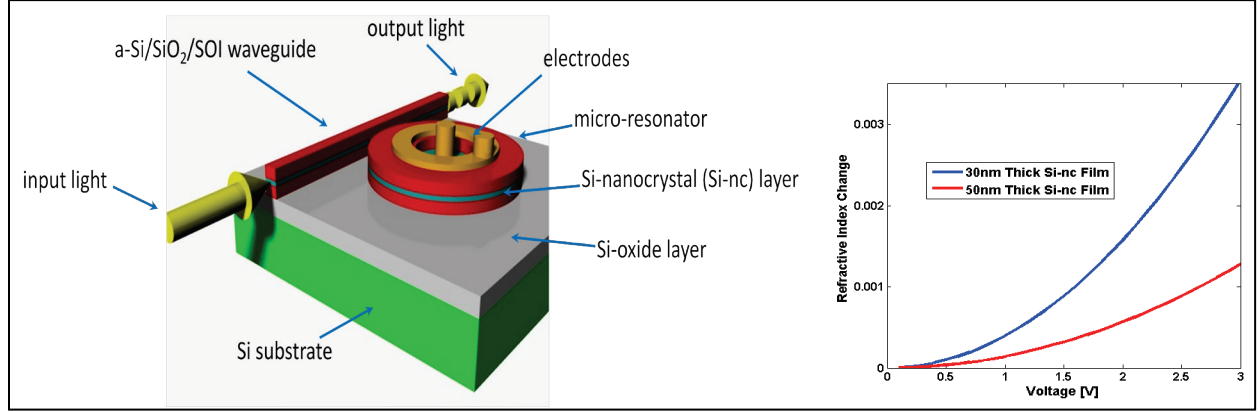


Figure 2. Proposed Kerr effect microring resonator modulator (left), and estimated index change vs. applied voltage (right).

3. Results

3.1 Nano-crystalline Film Generation

Several samples of Si-rich oxide films were deposited by reactively sputtering Si in the presence of oxygen, plasma enhanced chemical vapor deposition (PECVD), and low pressure chemical vapor deposition (LPCVD), as well as spin casting of hydrogen silsesquioxane (HSQ).

Annealing the films for various times resulted in the coalescence of Si-nc within the silicon dioxide (SiO₂) films. Photoluminescence of the samples show characteristic peaks near 800 nm (figure 3). Annealing these films at ~1100 °C for 1–2 min or more yields the highest intensity photoluminescence.

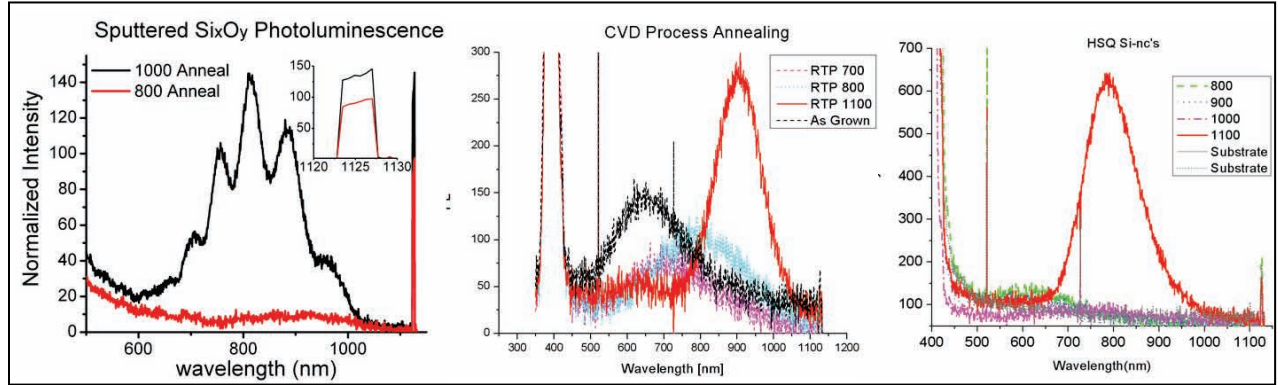


Figure 3. Typical measured ~800 nm Si-nc photoluminescence plots.

3.2 Kerr Nonlinearity Measurement Results

One method to measure the Kerr nonlinearity is via Z-scan (7). Z-scan setups consist of a high-power pulsed laser source focused to a small spot, through which the sample is passed (figure 4). A pinhole and detector are placed after the sample to capture a portion of the exiting light. Since the incident beam has a cross-sectional distribution of intensity, its electric field distribution induces a corresponding index change in the sample. This distribution induces a lensing effect in the sample, which alters the exiting beam shape. A change in the exiting beam shape predictably alters how much light passes through the pinhole and into the detector. Z-scan is a method typically used for measuring the nonlinear index and absorption coefficients in thick film and thin bulk samples; our sample (at ~100–500 nm) is extremely thin—the thinner the film, the weaker the lensing effect, and therefore the smaller the detectable change in transmission. The simplest way of overcoming this is to increase the instantaneous laser intensity by choosing a short pulse laser (<500 fs) with high peak pulse energy (>400 nJ) and short focus optics; we have performed measurements using just such a laser at ARL.

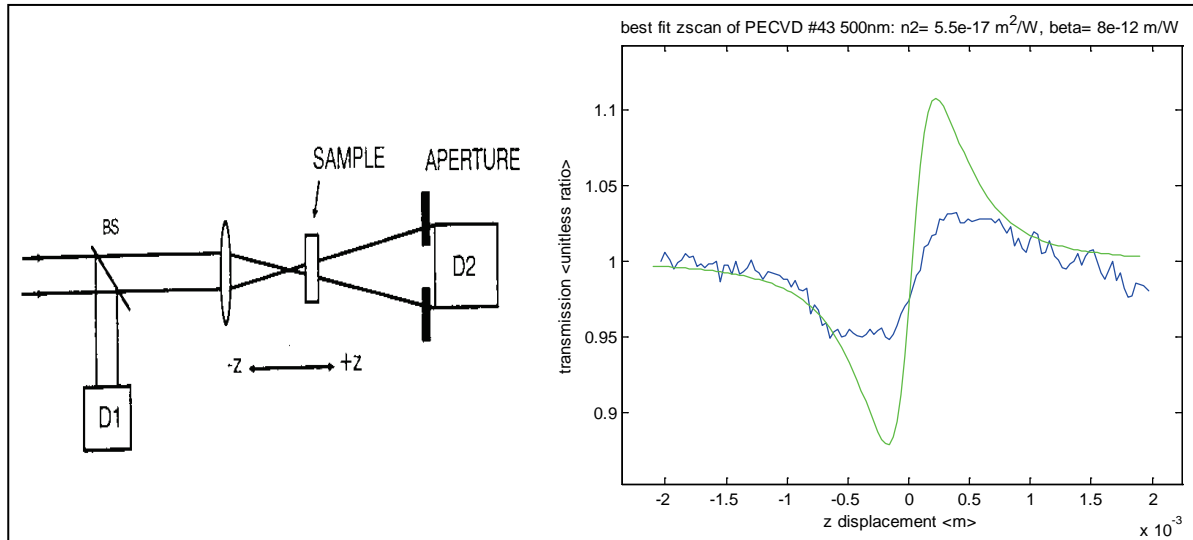


Figure 4. Z-scan measurement setup (left), simulated result (right [smooth line]), measured result (right [jagged line]).

Figure 4 (right) shows a measurement of a PECVD grown Si-nc film. The green line shows the best fit simulation using $n_2 = 5.5 \times 10^{-17} \text{ m}^2/\text{W}$ and $b = 8 \times 10^{-12} \text{ m/W}$, which matches well with what we expected. The clipping seen in the experimental data near to the focus (near zero z -displacement) is due to the laser's non-Gaussian beam shape. The beam's shape was tested by measuring its transmission through a pinhole translated through the focus. Figure 5 (green) shows the expected diffraction-limited transmission of the high-power free-space laser (left) and a low-power fiber pigtailed laser (right)—the experimental results are shown in blue. The high-power free-space laser does not focus down to the expected diffraction-limited spot size, this causes the clipping observed in figure 4.

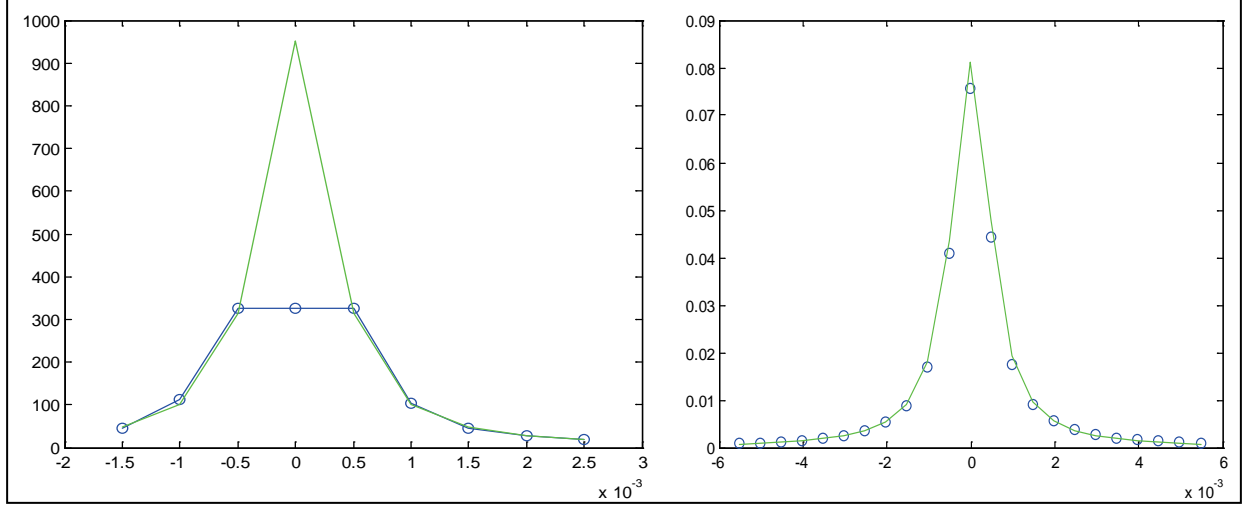


Figure 5. Diffraction-limited focused beam transmission through a translated pinhole (left [green]), measured transmission (left [blue]), expected and measured transmission of fiber pigtailed (nearly diffraction-limited beam) (right).

Two other methods were investigated using the ideally shaped but lower powered fiber laser when the high-power free-space laser was unavailable. One method was based on dithering the sample along the z -axis as it was being scanned, while a lock-in amplifier measured the response on the transmission detector. The result seen by the transmitted detector would be the differentiation of the curve seen in figure 4. By locking the amplifier into the sample's dithering frequency, the signal-to-noise ratio of the experiment could be greatly improved. The second method simply chopped the incoming light and carefully matched the response shape of the transmission and reference beams' detectors and measuring the difference with a differential lock-in amplifier. Unfortunately, these efforts had to be abandoned after exhaustive testing revealed that the fiber laser's low power simply could not overcome the sample's lateral variations in linear transmission. Efforts were then refocused on obtaining a more ideal beam shape using the high-power free-space laser, but being a shared resource, these efforts were incomplete as of this writing.

4. Conclusions

Advancing the understanding of the Si-nc's Kerr effect will lead to significantly improving Si-based optoelectronic devices. The proliferation of Si CMOS-compatible optical modulators will significantly improve processor performance and sensor data communications in Army (and eventually civilian areas as well) computationally intensive applications. Si CMOS-compatible

modulators, waveguides, and detectors integrated with FPGAs will enable extremely high-performance processing. This is increasingly important as the sensors on fuzes, missiles, ground, and airborne platforms become more advanced, increasing the complexity of signal and image processing.

We were able to produce Si-nc films as well as measure their Kerr nonlinearity. Efforts are ongoing to improve our nonlinearity measurement setup.

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6. Transitions

Stefan Preble is continuing this effort at RIT. We plan on improving the beam quality of the high-power laser to continue our Kerr nonlinearity measurement efforts. If successful, we plan on submitting our findings to *Optics Letters*. We will also continue our efforts to fabricate sub-micron structures using ARL's e-beam lithography system.

List of Symbols, Abbreviations, and Acronyms

ARL	U.S. Army Research Laboratory
CMOS	complementary metal-oxide semiconductor
FPGAs	field programmable gate arrays
GPUs	graphical processor units
HSQ	hydrogen silsesquioxane
InGaAsP	indium gallium arsenide phosphide
LiNbO ₃	lithium niobate
LPCVD	low pressure chemical vapor deposition
PECVD	plasma enhanced chemical vapor deposition
RIT	Rochester Institute of Technology
Si	silicon
Si-nc	silicon-nanocrystals imbedded in oxide
SiO ₂	silicon dioxide
TEM	transmission electron microscopy
WDM	wavelength-division multiplexing

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